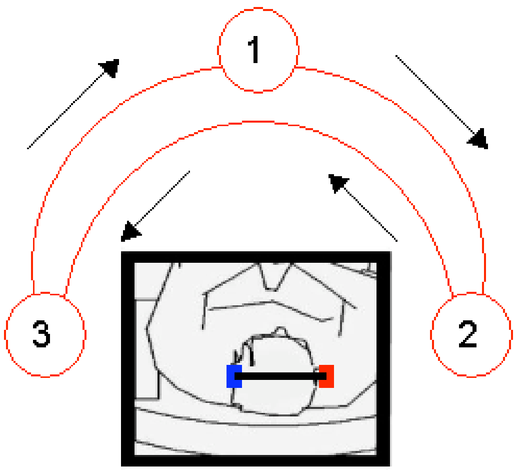
BINAURAL HEARING and INTELLIGIBILITY in AUDITORY DISPLAYS



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1. Binaural hearing phenomena

2. Newly developed auditory displays
   that exploit spatial hearing for improving

   -speech intelligibility
   -alarm intelligibility

in aviation applications

Physical characteristics of sound and perceived attributes

- **F**requency → (perceived pitch)
- **I**ntensity → (loudness)
- **S**pectral content → (timbre)
- **FIS**, plus binaural differences → (localization)

Physical characteristics of sound and perceived attributes

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- **S**pectral content → (timbre)
- **FIS**, plus binaural differences → (localization)

** All characteristics are important in the identification and discrimination of auditory signals and for speech intelligibility in communication contexts

Two important functions of the binaural hearing system

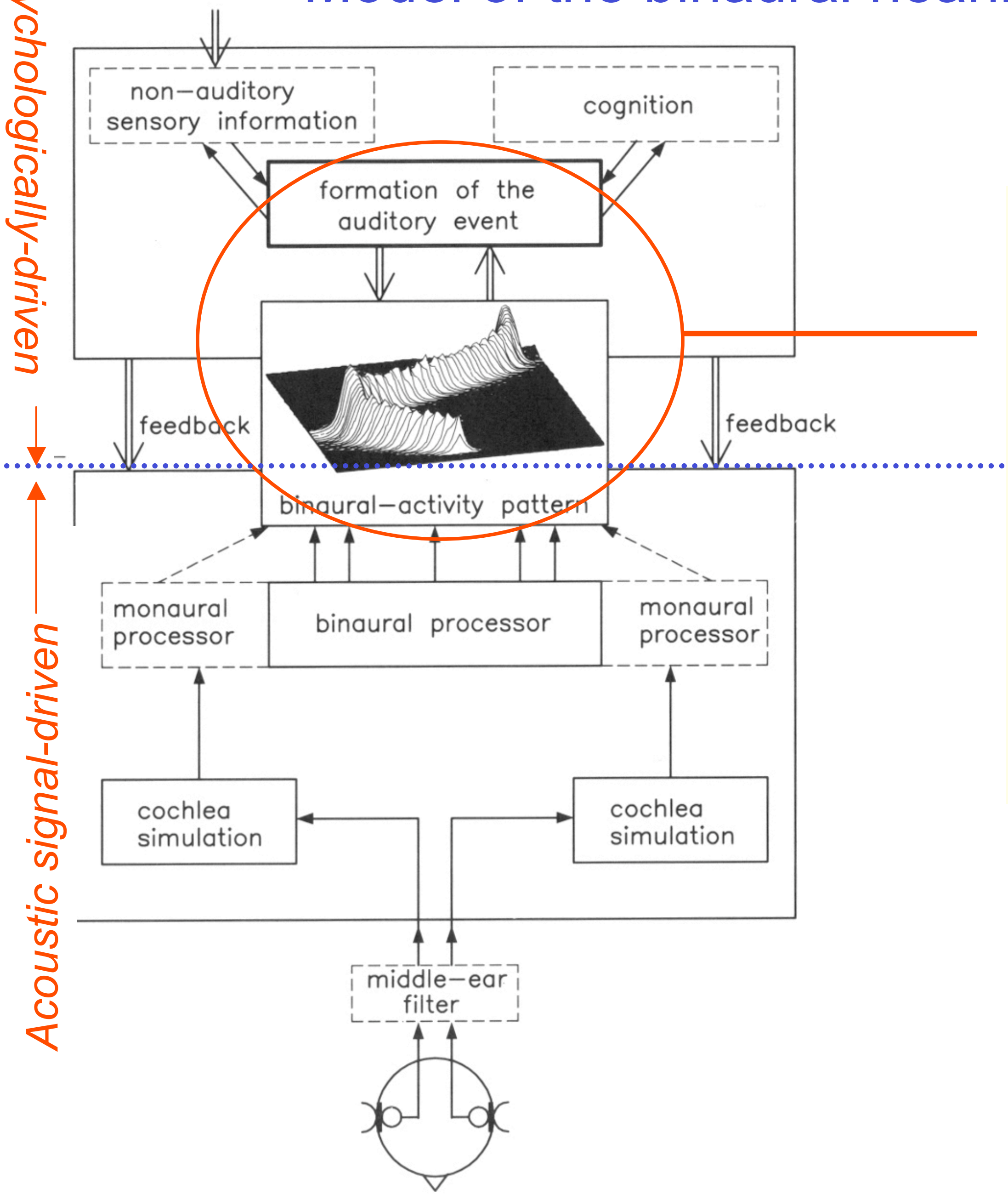
- Localization

  (lateral and 3-dimensional)

- Binaural release from masking:

  Echo supression, room perception

Model of the binaural hearing system



Psychologically-driven

Acoustic signal-driven

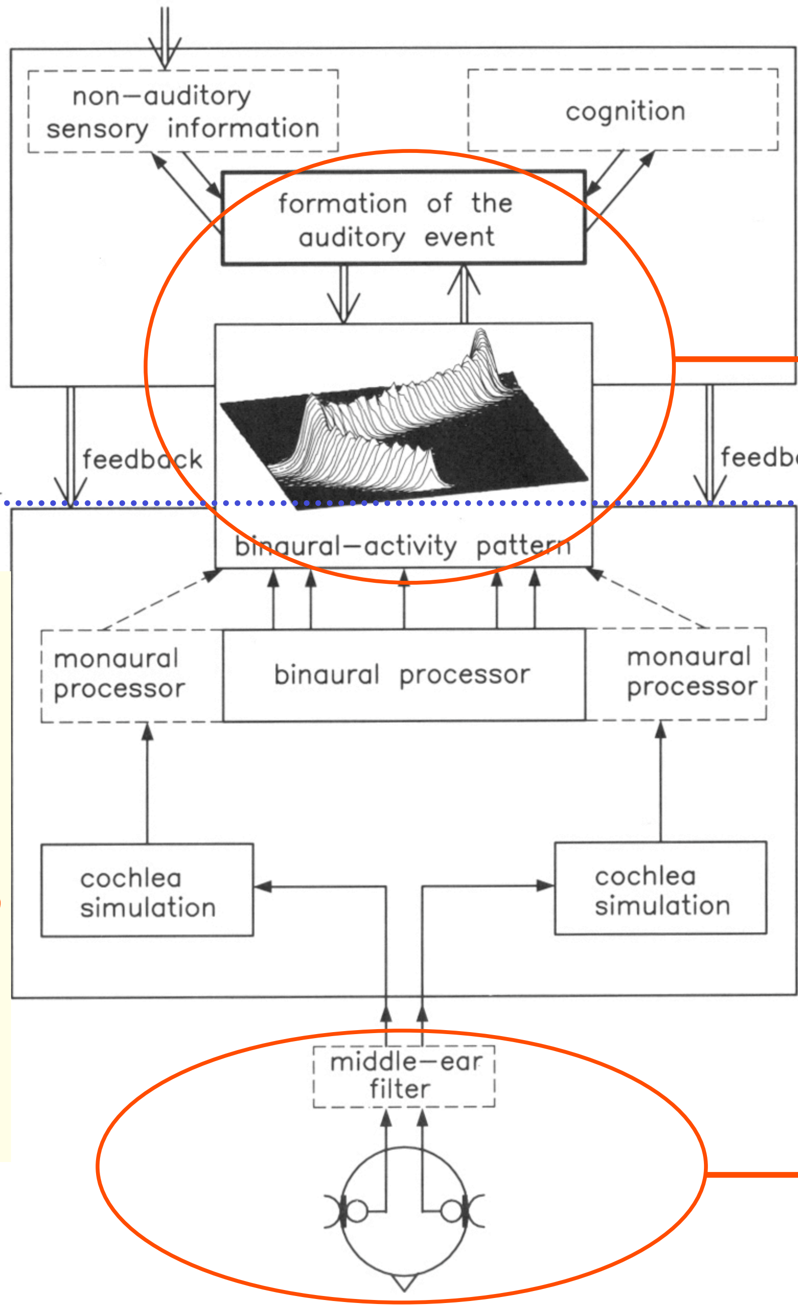
Binaural hearing (localization; signal separation & detection):

forming spatial auditory events from acoustical (bottom-up) and psychological (top-down) inputs

Model of the binaural hearing system

Psychologically-driven

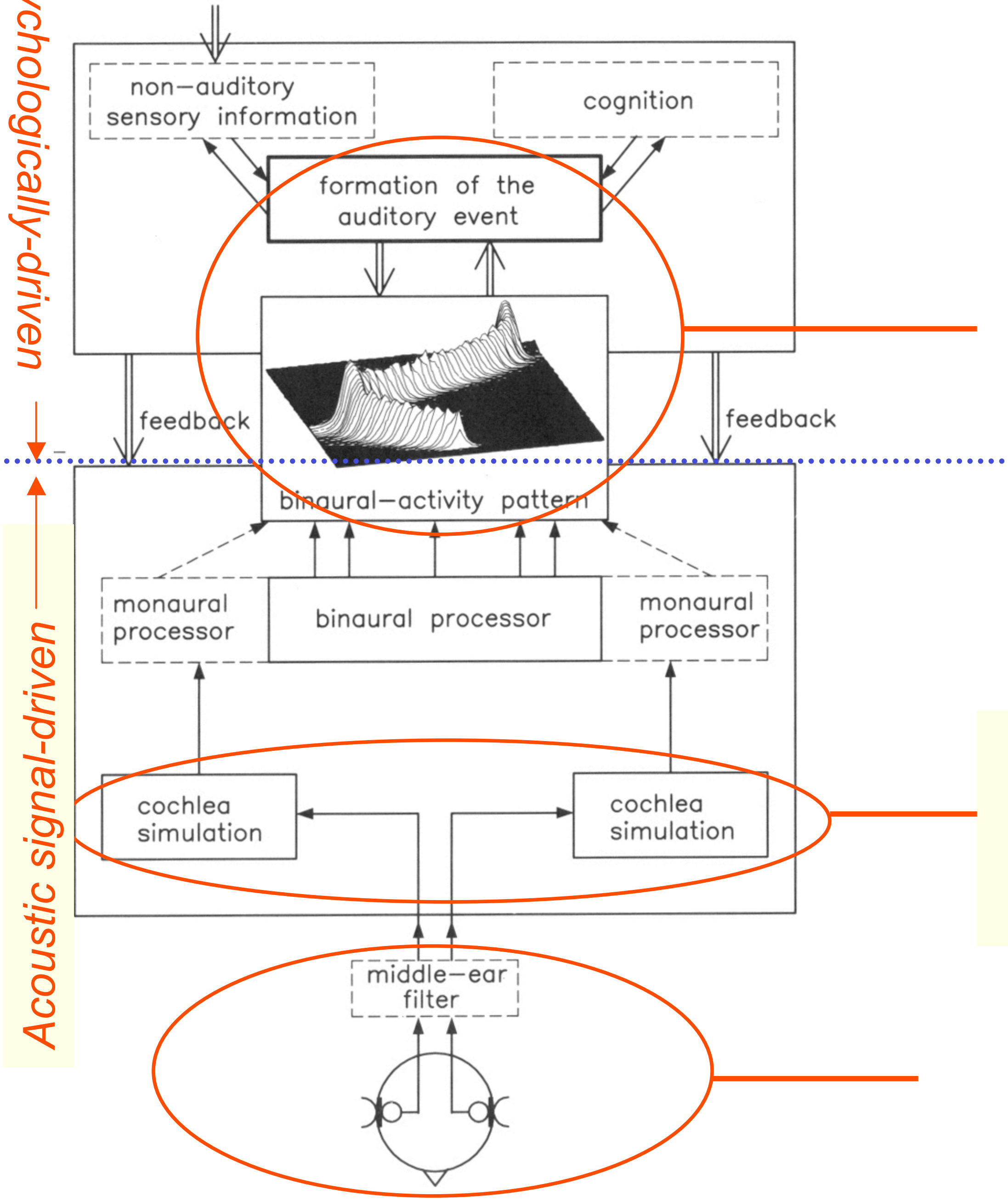
Acoustic signal-driven



Binaural hearing (localization; signal separation & detection)

Filtering of acoustic signal by pinnae, ear canal

Model of the binaural hearing system

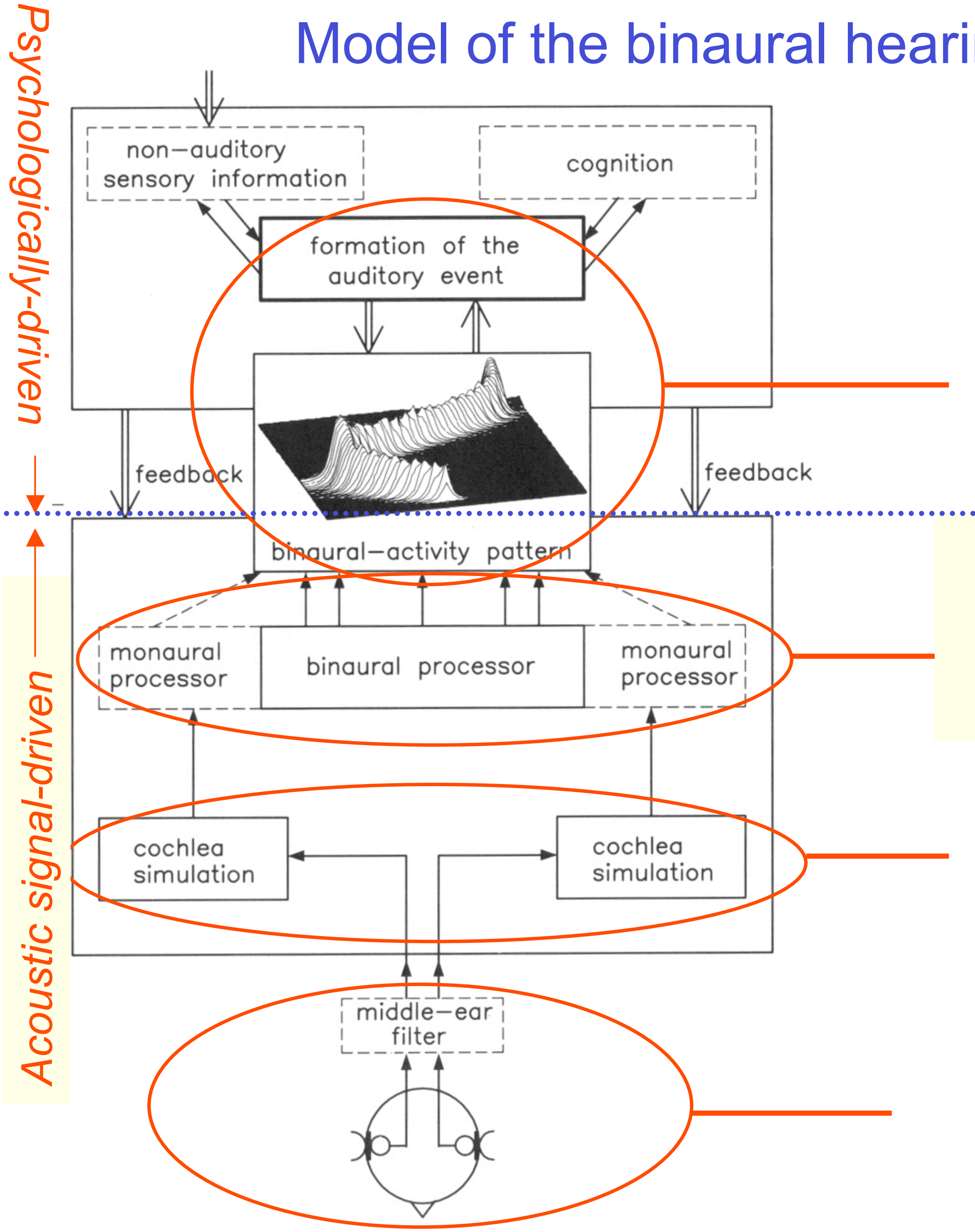


Binaural hearing (localization; signal separation & detection)

Filtering by inner ear; frequency-specific neuron firings

Filtering of acoustic signal by pinnae, ear canal

Model of the binaural hearing system



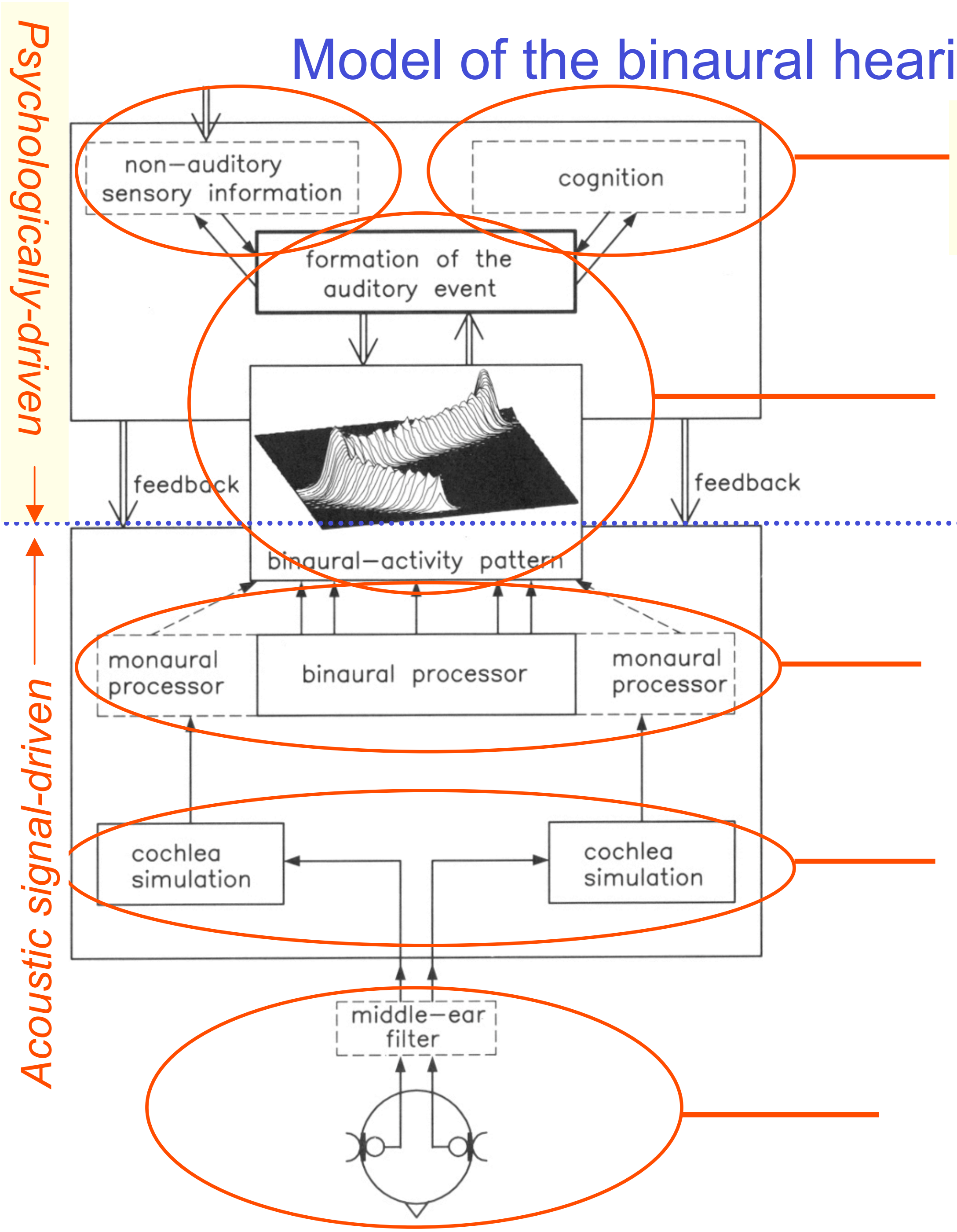
Binaural hearing (localization; signal separation & detection)

Physiological evaluation of interaural timing and level differences

Filtering by inner ear; frequency-specific neuron firings

Filtering of acoustic signal by pinnae, ear canal

Model of the binaural hearing system



Multi-sensory information; cognition

Binaural hearing (localization; signal separation & detection)

Physiological evaluation of interaural timing and level differences

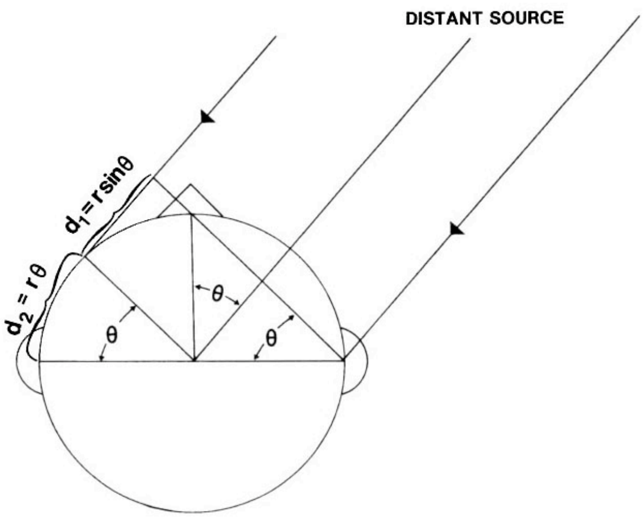
Filtering by inner ear; frequency-specific neuron firings

Filtering of acoustic signal by pinnae, ear canal.

Lateral localization of auditory images

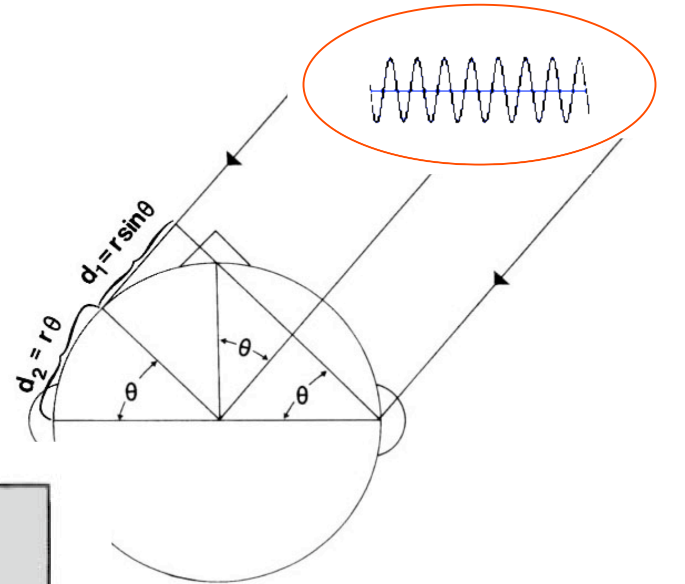
“Duplex” theory of localization

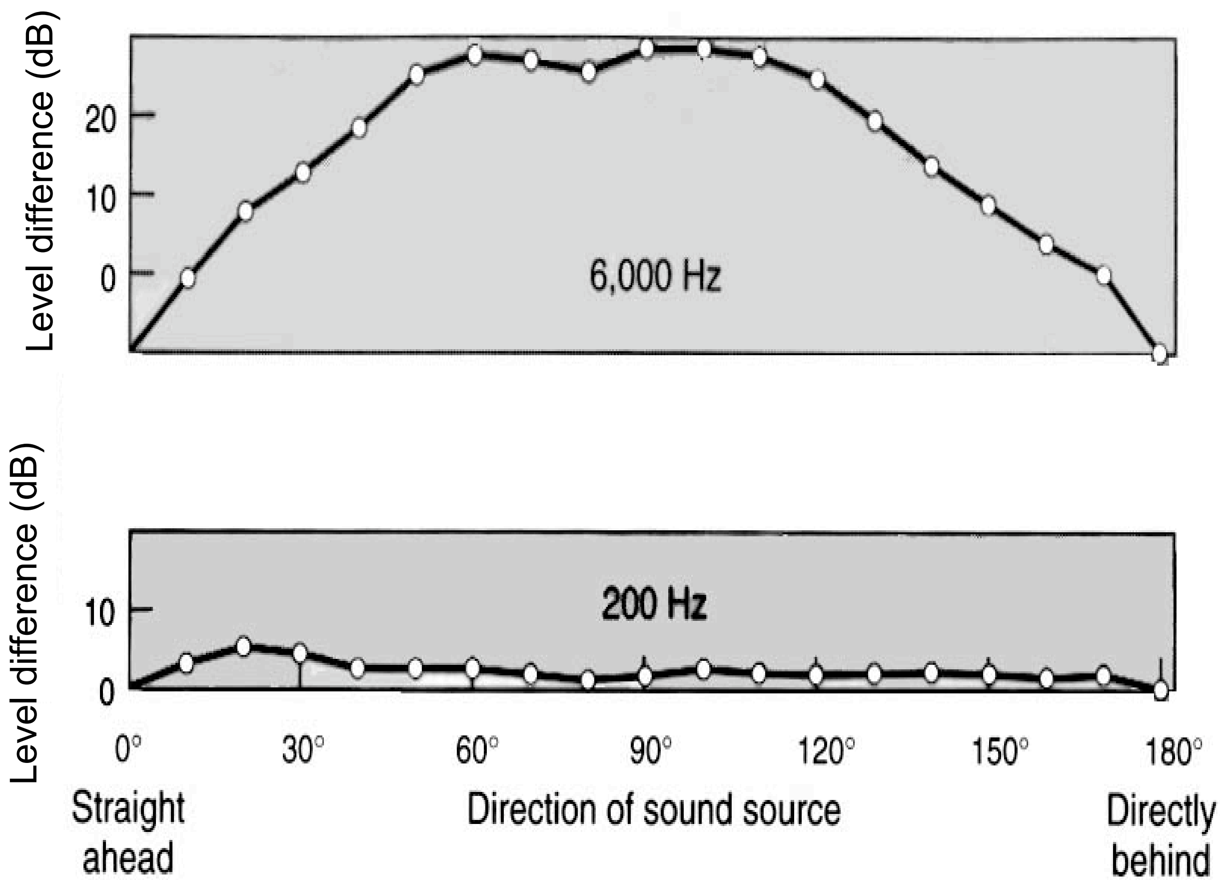
- ILD (interaural level difference)
- ITD (interaural time difference)



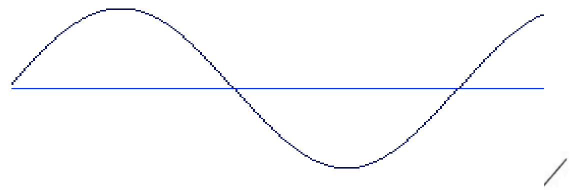
Lateral spatial image shift

- ILD (interaural level difference) caused by head shadow of wavelengths > 1.5 kHz

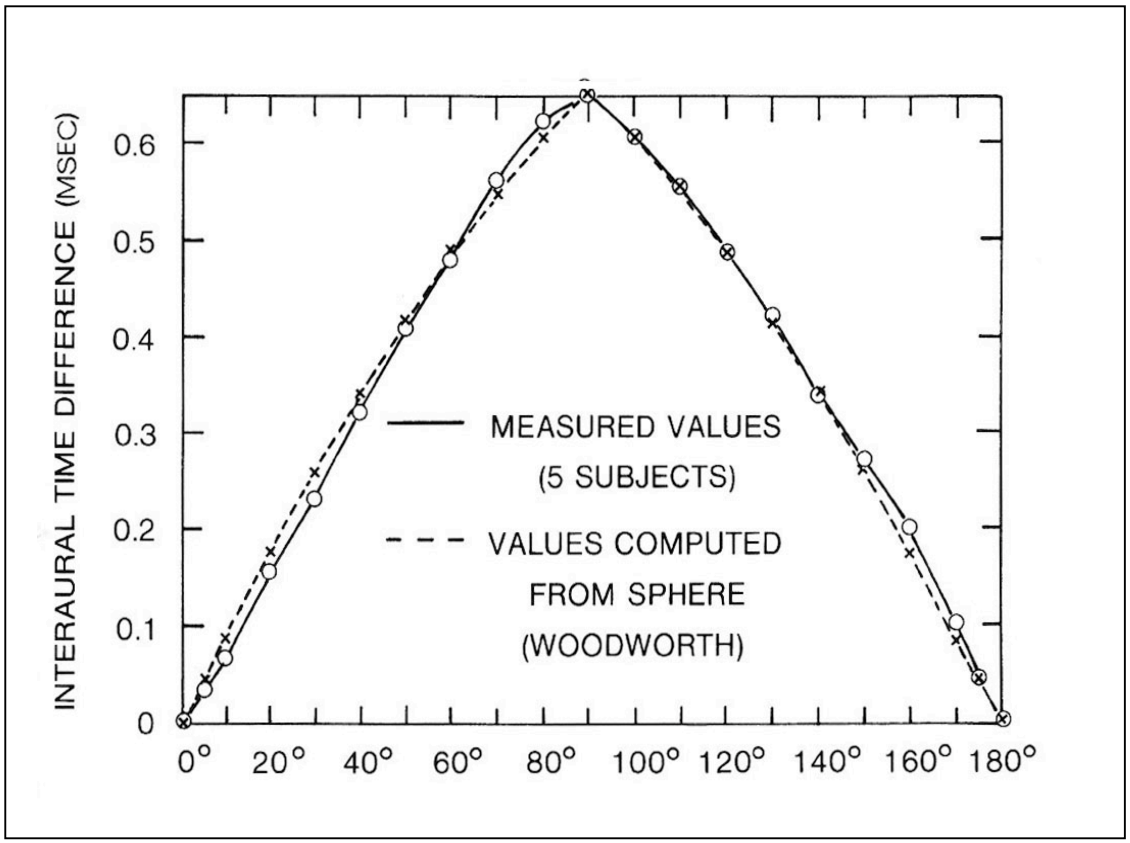


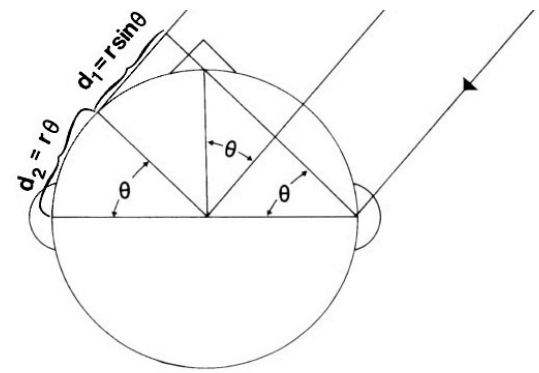


Lateral image shift

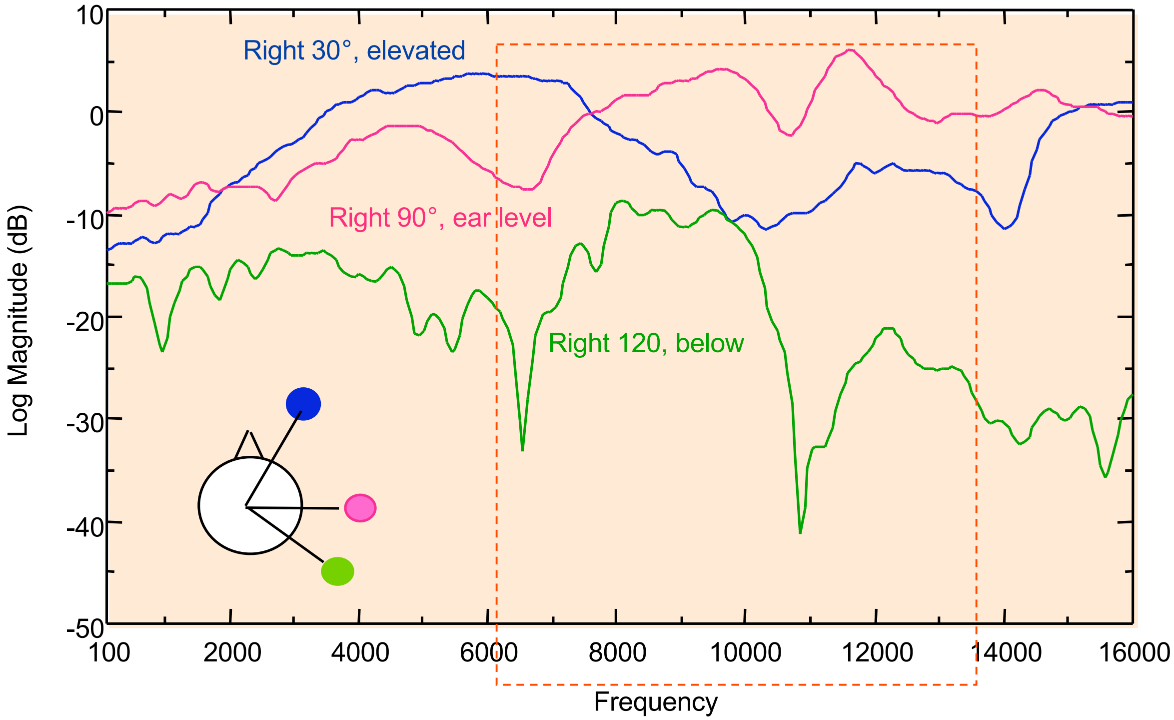


- ITD (interaural time difference)

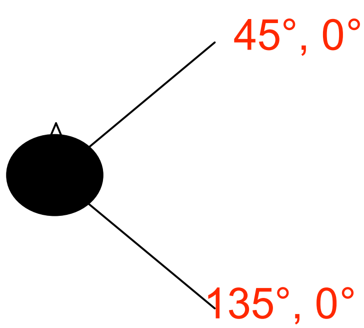


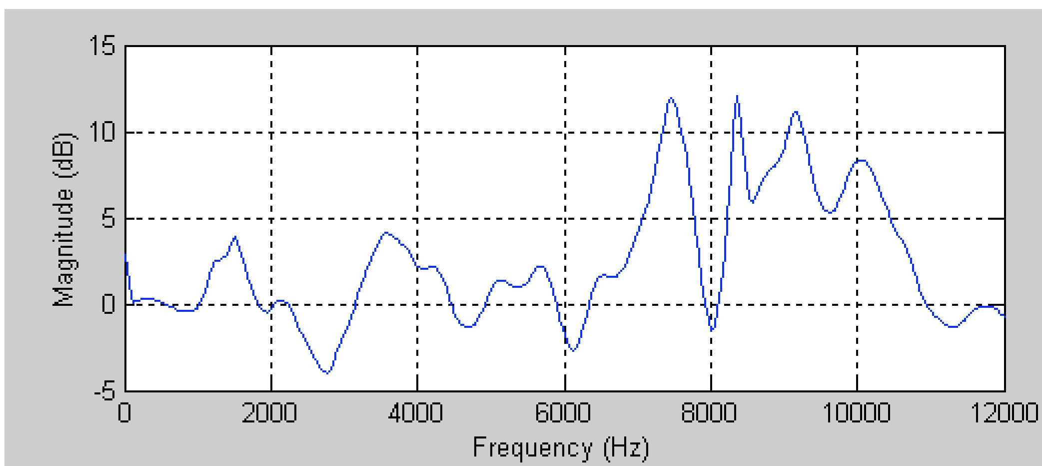


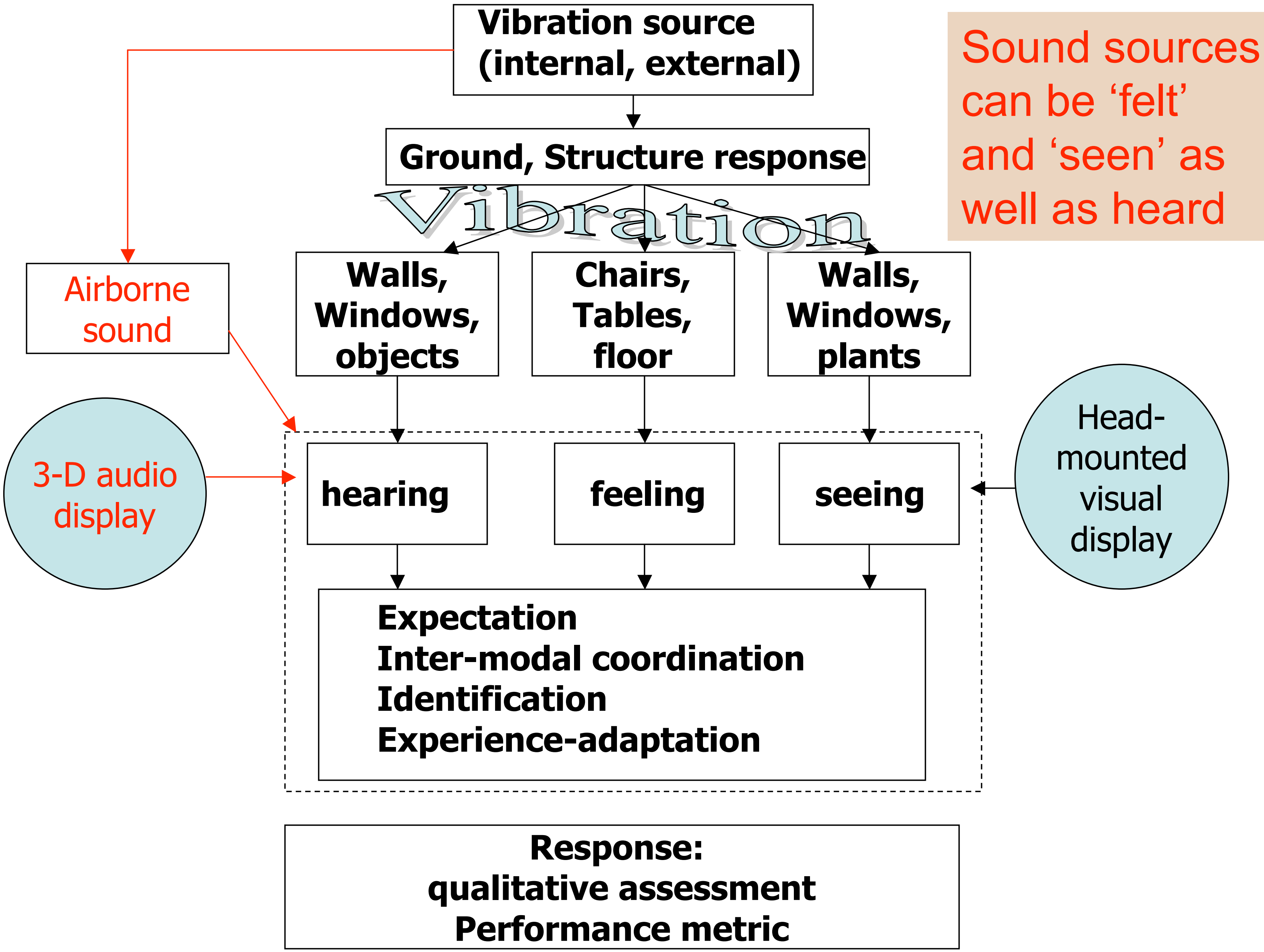
Head-related transfer function cues (HRTFs) provide cues for front-back discrimination and elevation



Basis of 3-D audio signal processing in auditory displays



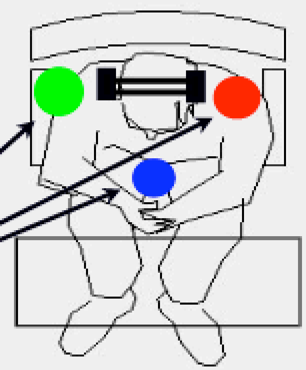



Vibration source
(internal, external)
Ground, Structure response
Vibration
Airborne sound
Walls, Windows, objects
Chairs, Tables, floor
Walls, Windows, plants
3-D audio display
hearing
feeling
seeing
Head-mounted visual display
Expectation
Inter-modal coordination
Identification
Experience-adaptation
Response:
qualitative assessment
Performance metric
Sound sources can be 'felt' and 'seen' as well as heard

Applications of spatial sound for improving intelligibility in auditory displays

Using binaural hearing advantage for separating multiple auditory "streams" (simultaneous sources)

Proposed 3-D audio communication system



Each communication channel is spatially separated.

User can use selective attention to switch between signals, as in normal hearing.

Background noise reduced via on-the-ear, active noise cancellation headsets.

Normal communication still possible without intercom

* Improved intelligibility

* Less fatigue

3-D communication system patented, developed for NASA-KSC

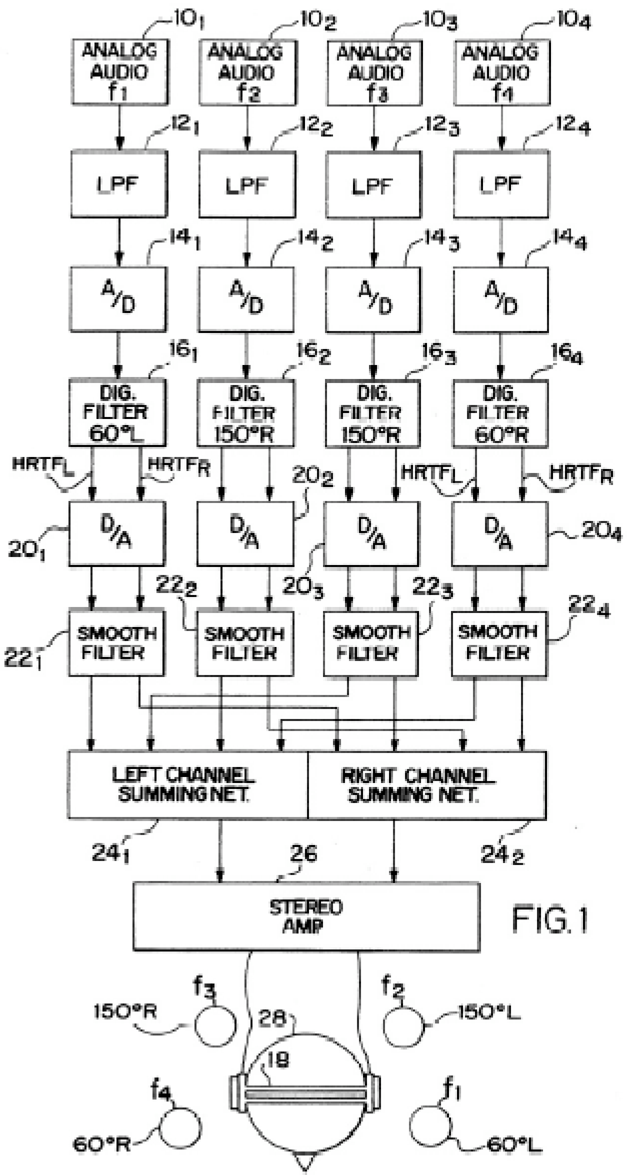


FIG.1

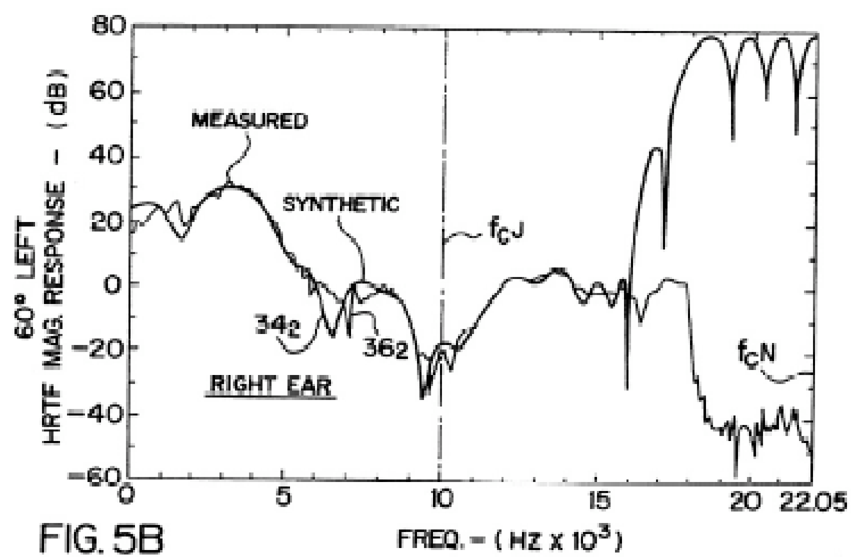
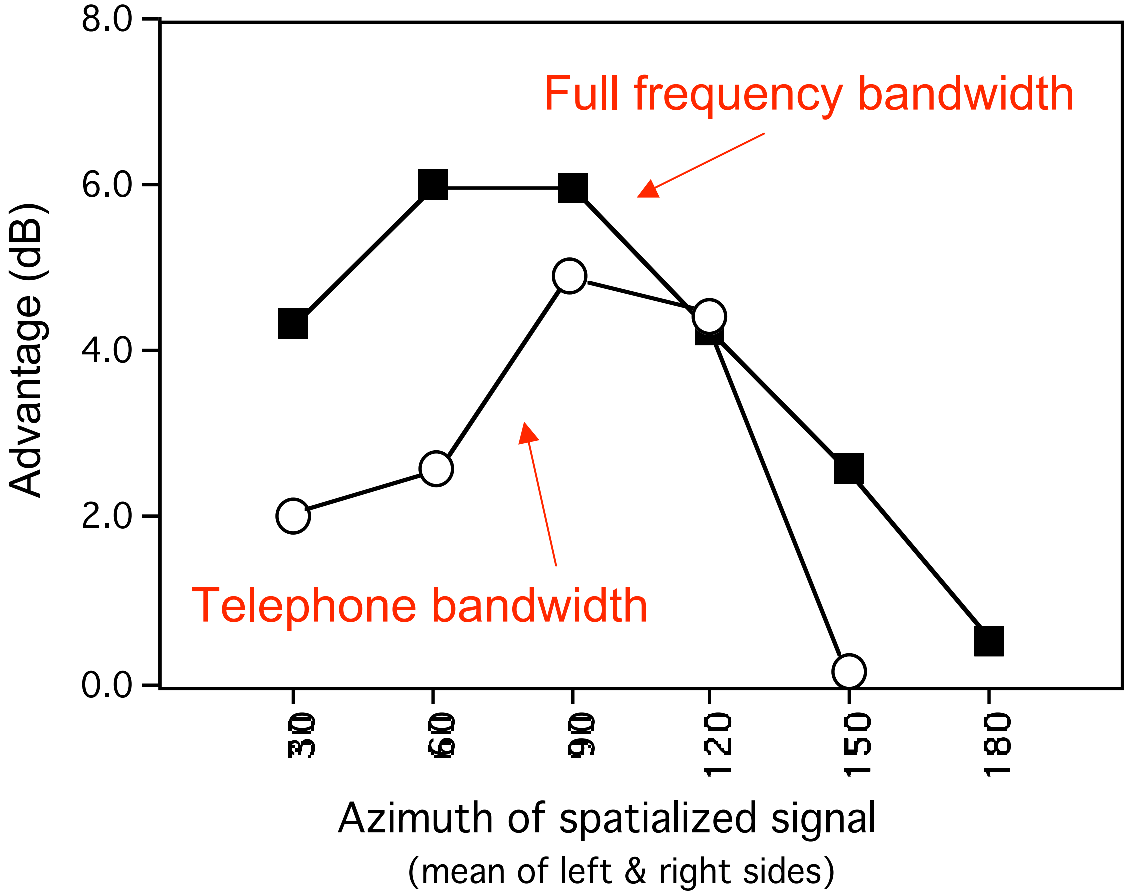
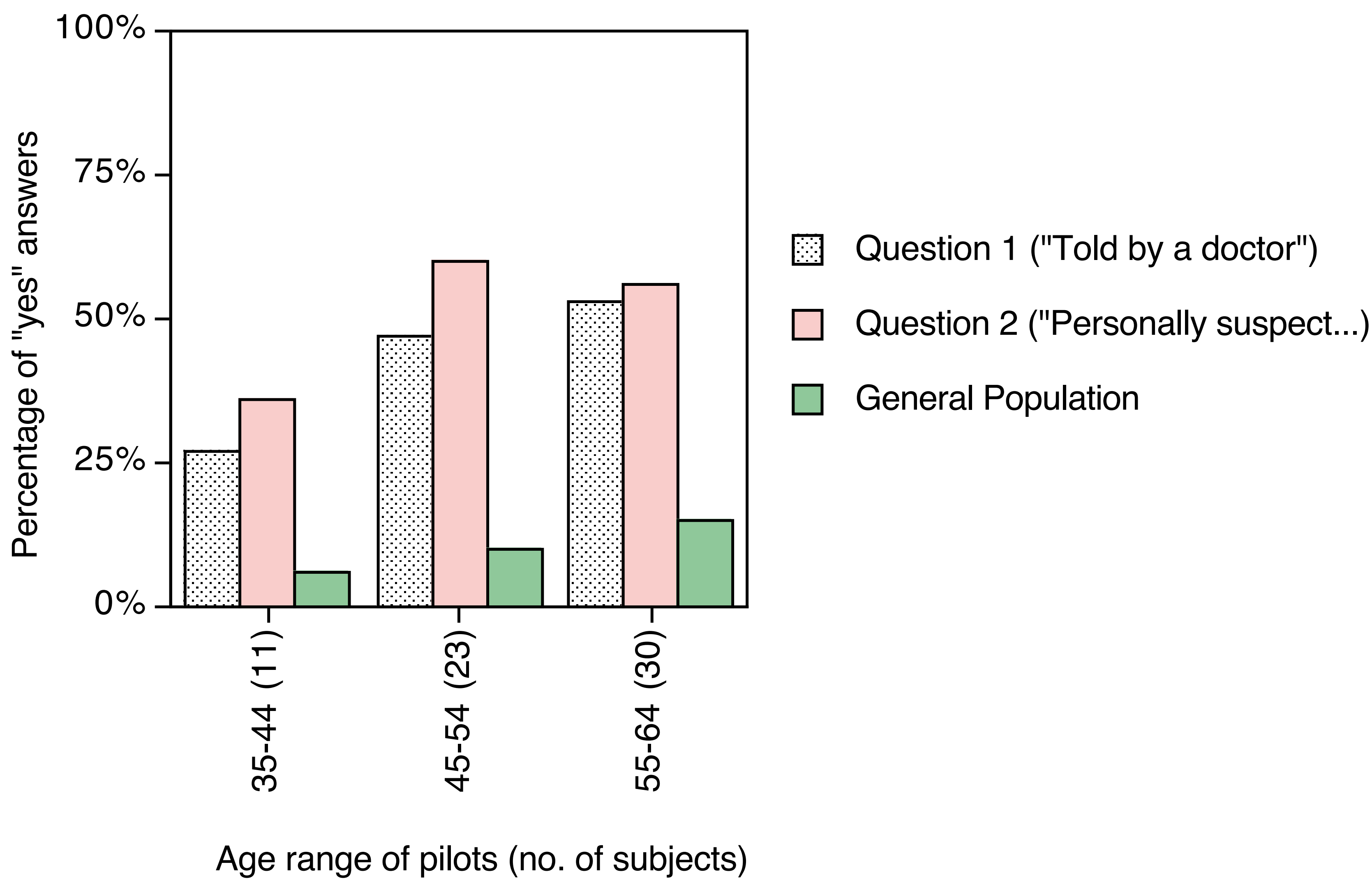


FIG. 5B

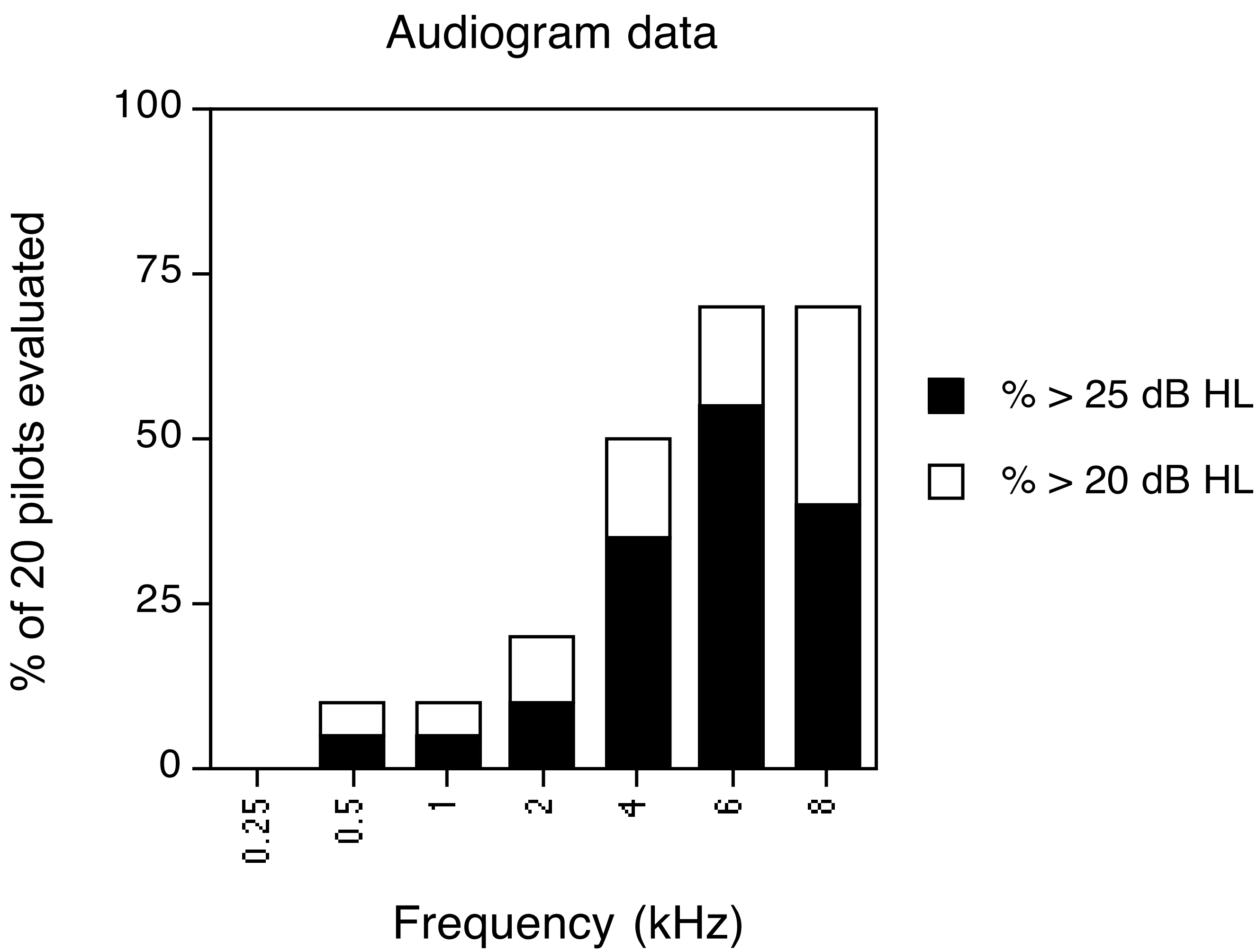
Speech Intelligibility advantage compared to one-ear listening



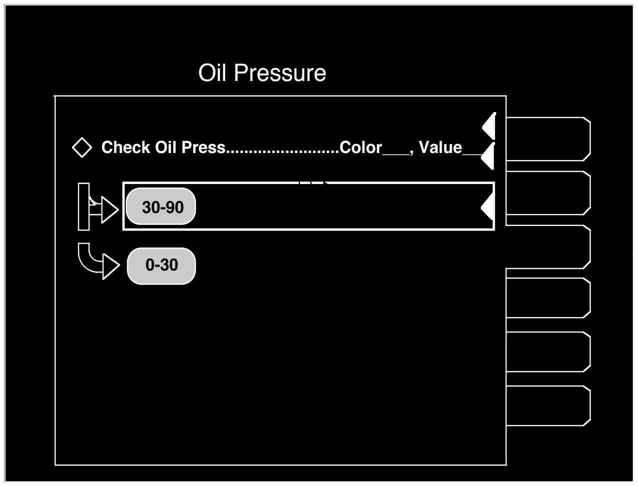
Hearing loss for target users: 64 active commercial airline pilots



Audiogram data summary for 20 active commercial pilots (age range 35-64; not corrected for presbycusis)

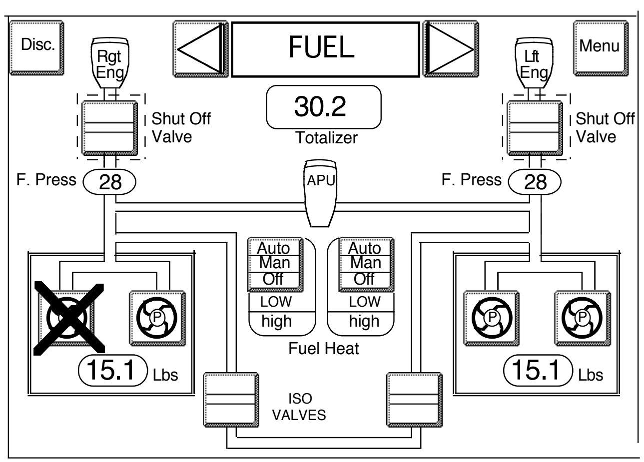


Use of auditory icons (AI) and left-right spatialization for information redundancy, situational awareness of actions of crew (CRM) and haptic feedback substitution



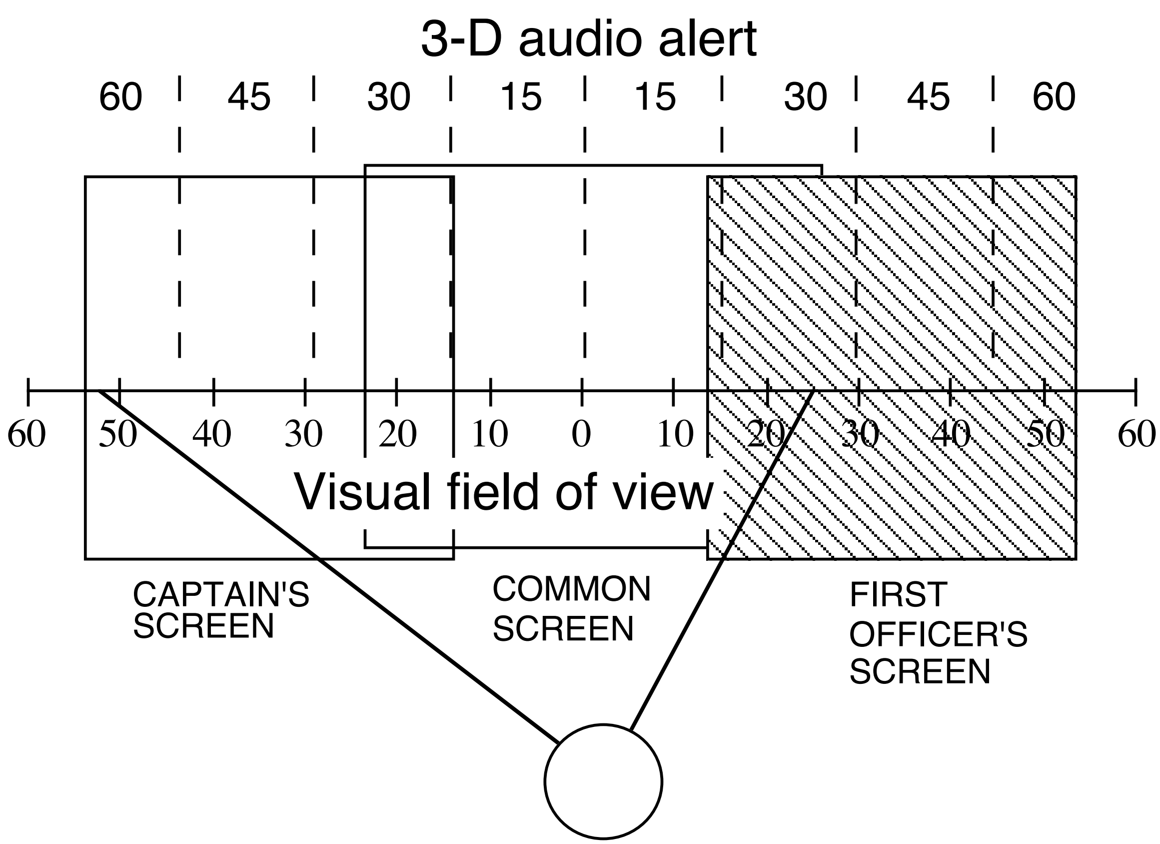
"Page-through" & "switch" AIs for touch screen checklist

NASA ARC advanced cab simulator



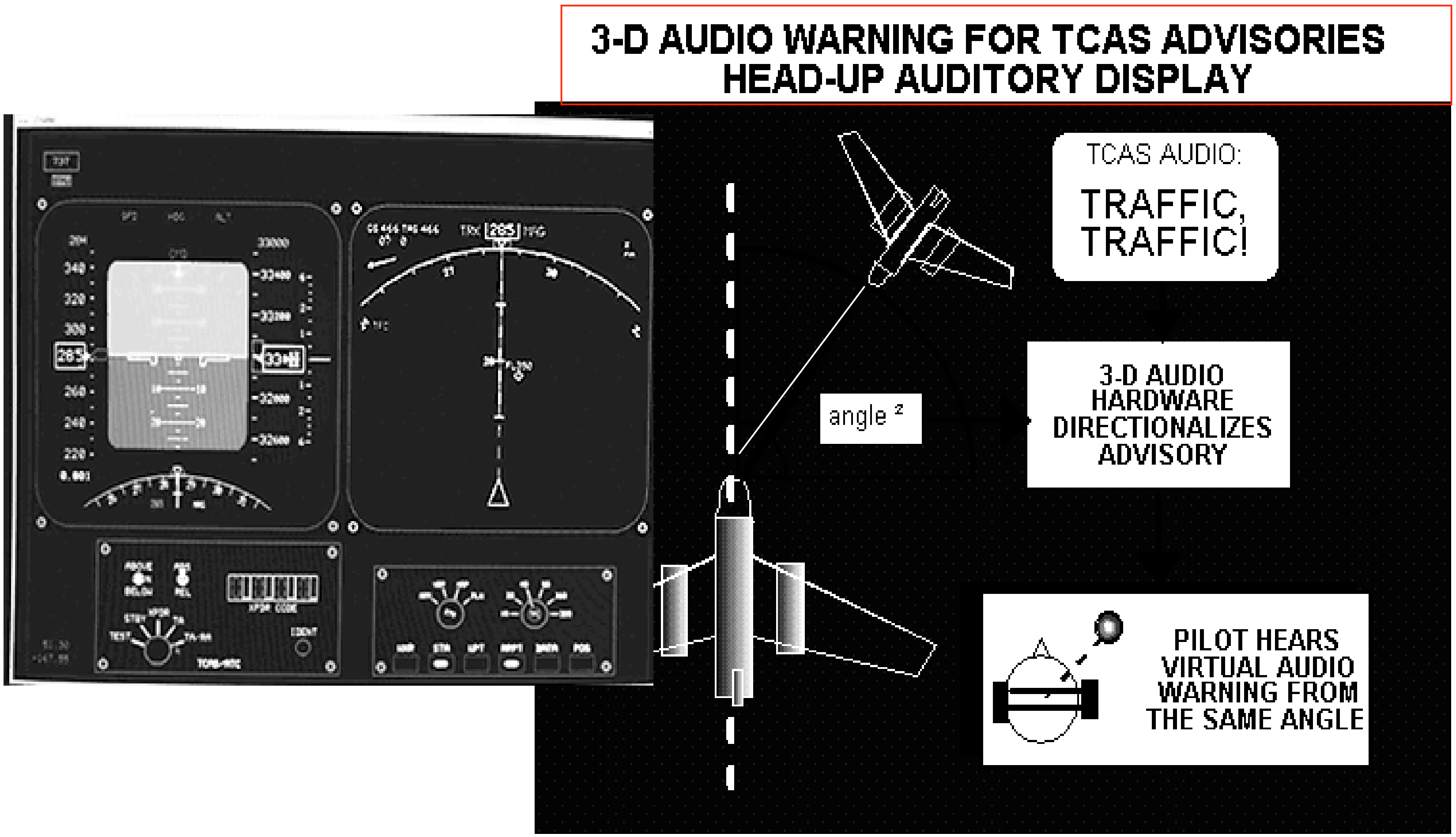
"Mechanical latch" AIs for actions corresponding to electrical, fuel, hydraulic systems

Head up auditory display for TCAS



Application of 3-D audio head-up display for Traffic Collision Avoidance System (TCAS II) investigated.

Target acquisition times can decrease from 0.5 – 2.2 sec.

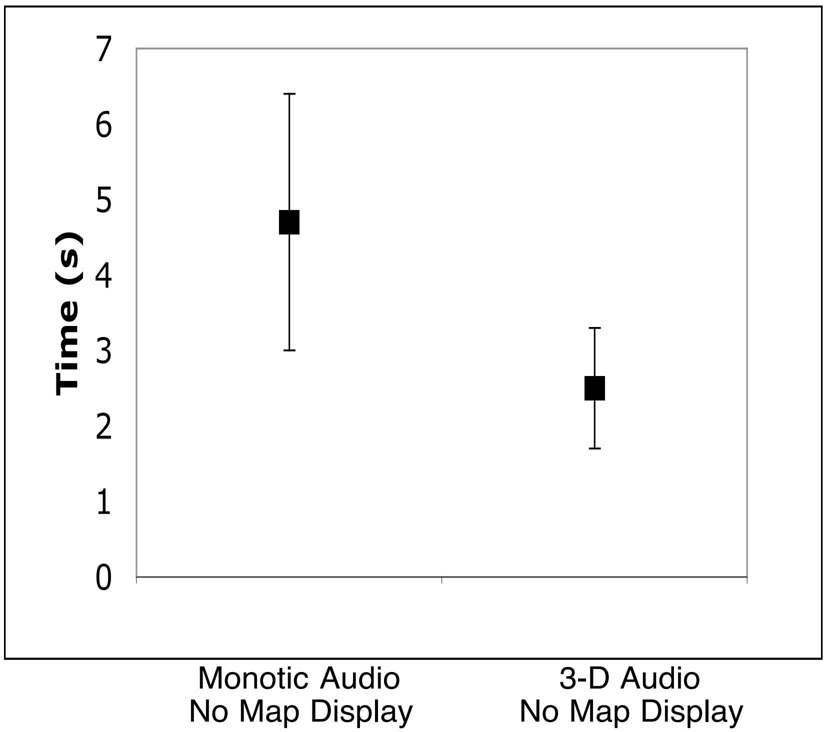


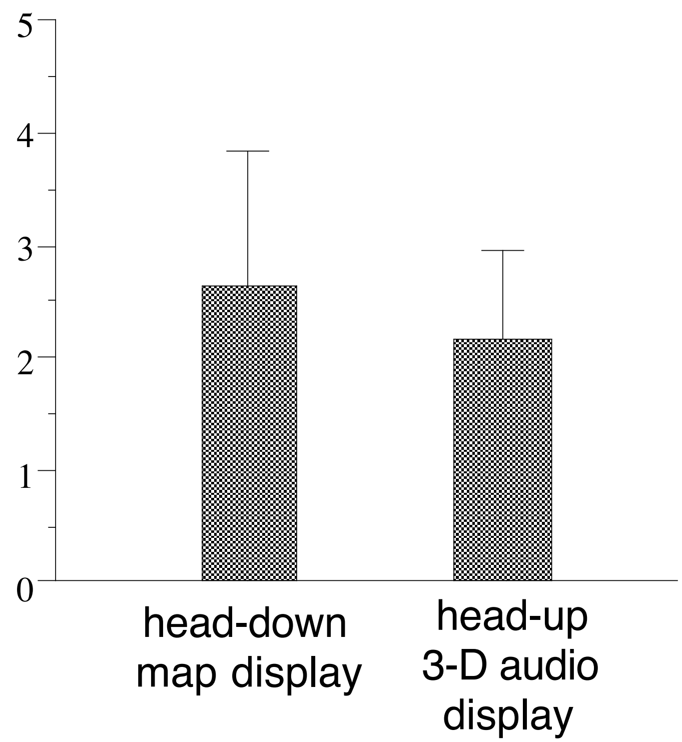
Mean target acquisition times (4.7 vs. 2.5 s) and standard deviations for first TCAS experiment.

The 3-D audio cues were exaggerated in azimuth relative to the visual target, and no elevation cues were supplied.

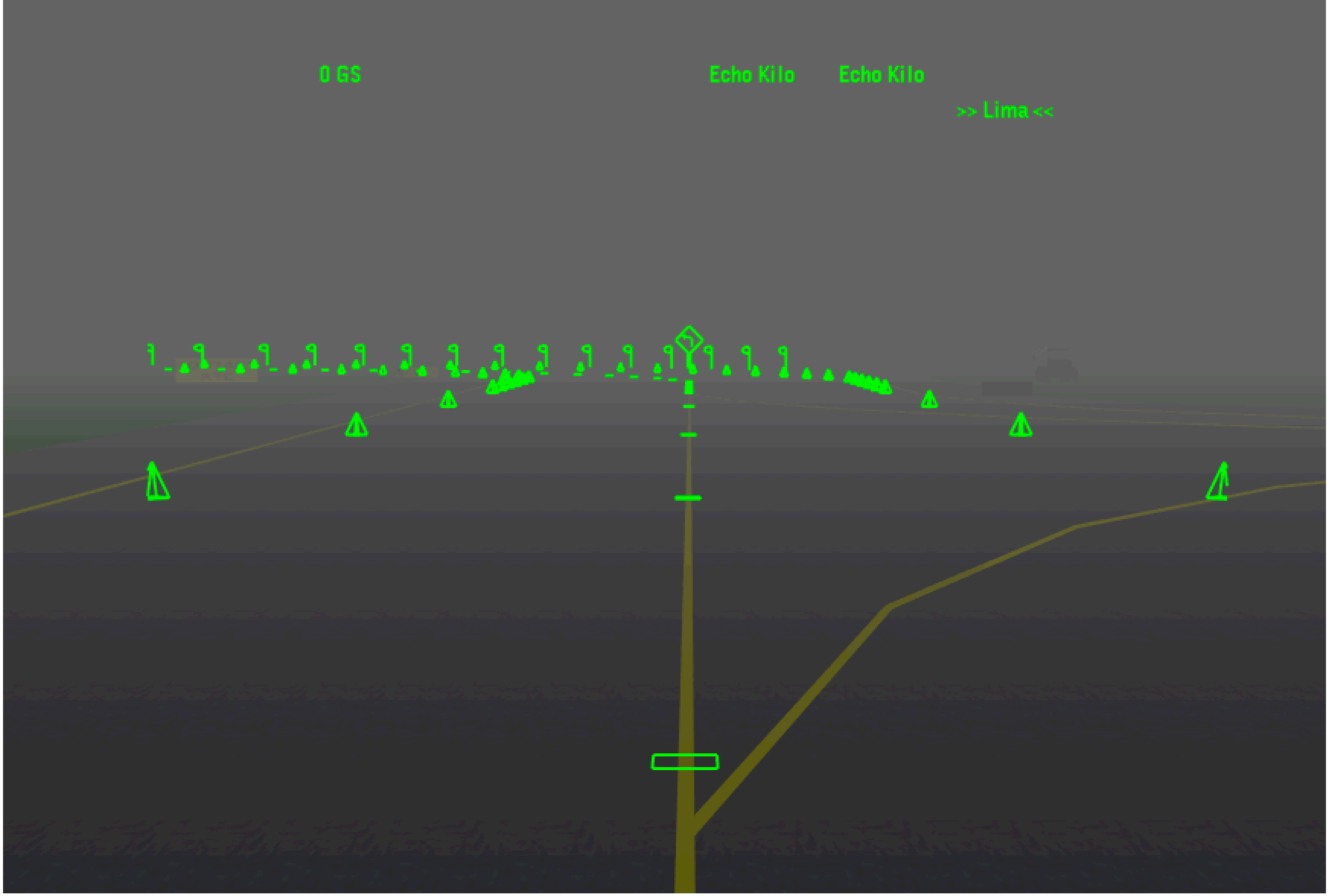
Mean target acquisition times (2.63 vs. 2.13 s) and standard deviations for second TCAS experiment.

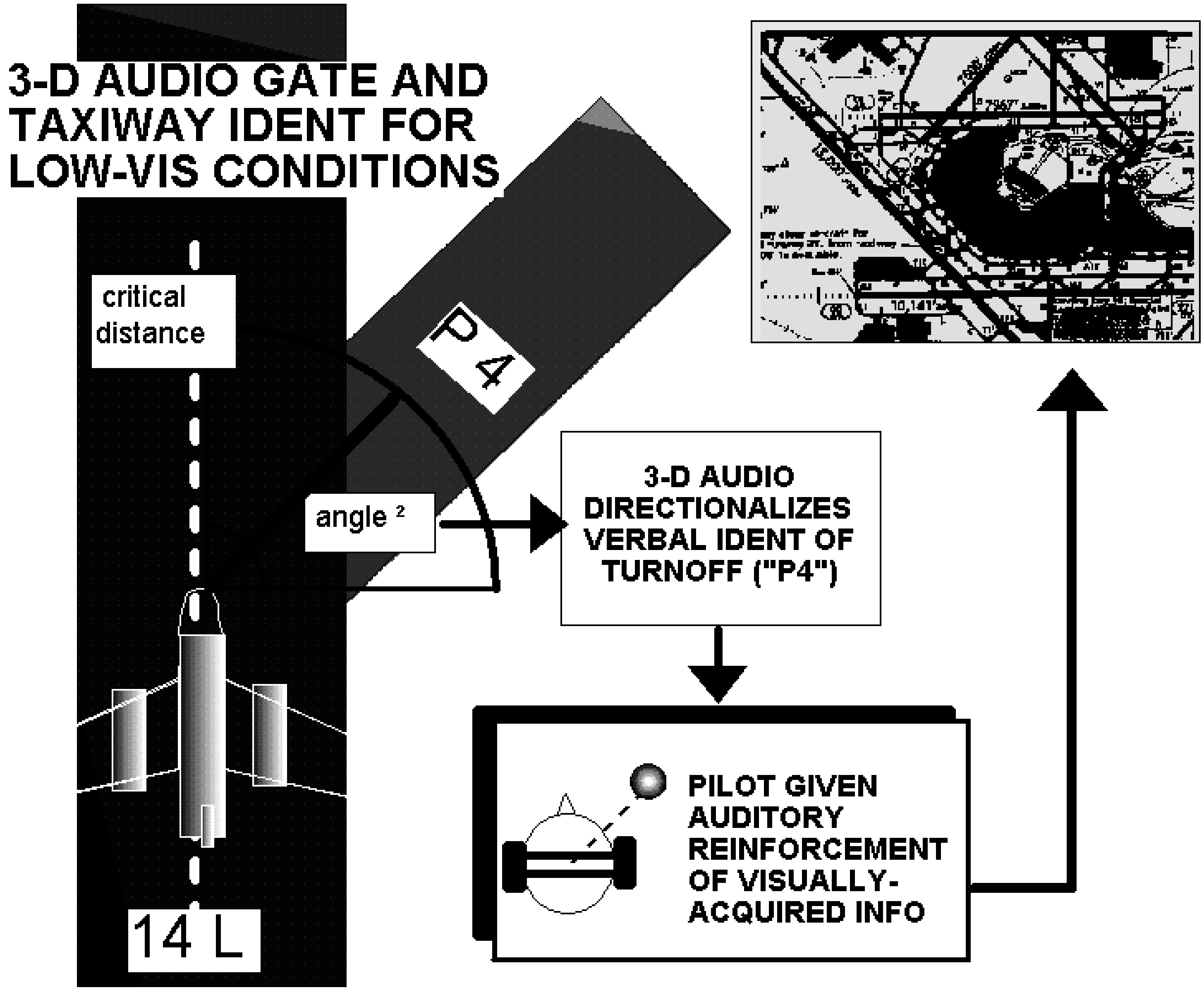
The 3-D audio cues were not exaggerated, and there were three categories of elevation cues.



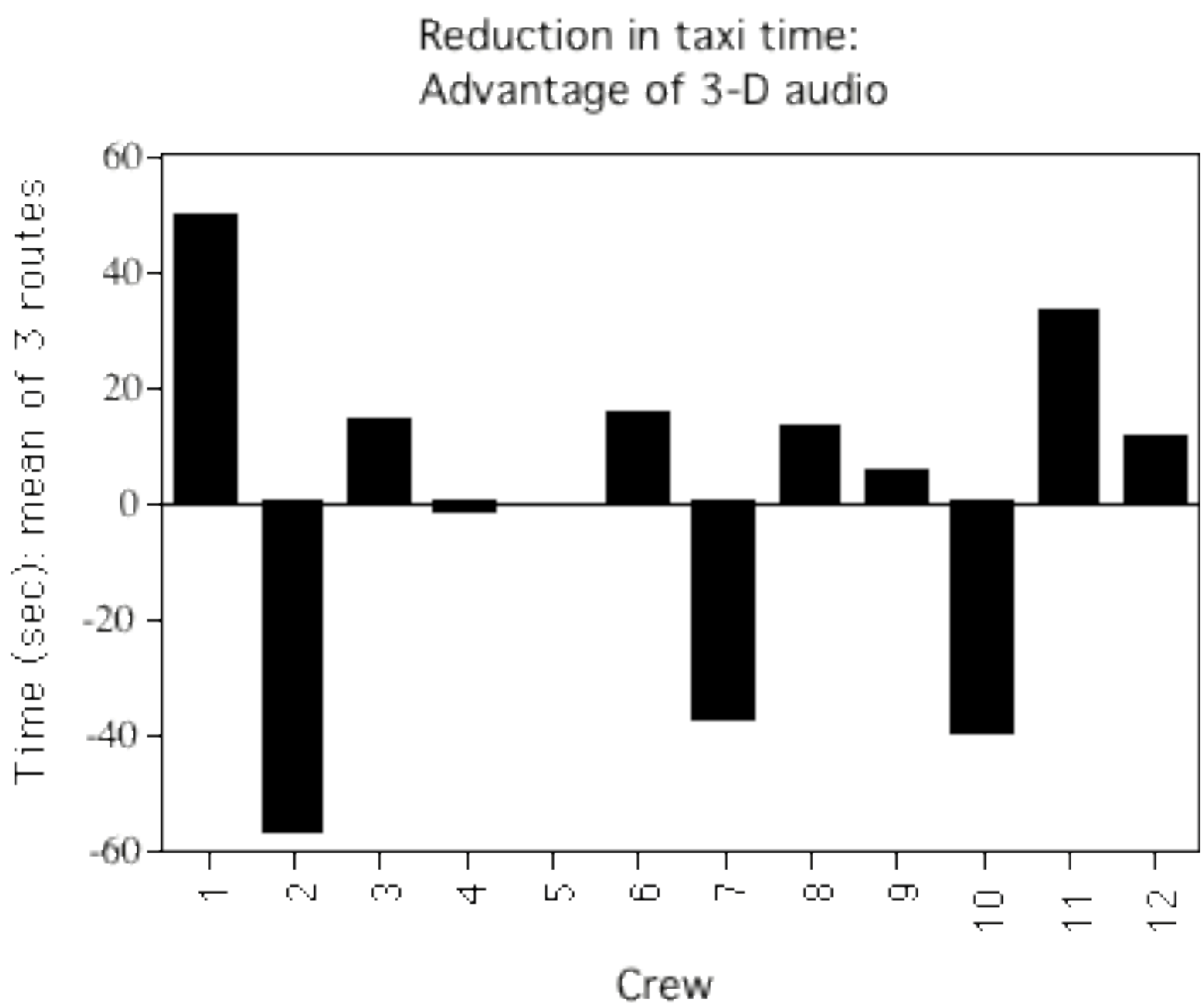


Head-up auditory display with head-up visual display





Application of 3-D audio head-up display for taxiway turnoff guidance


Reduction in taxi time:
Advantage of 3-D audio
Time (sec): mean of 3 routes
60
40
20
0
-20
-40
-60
1
2
3
4
5
6
7
8
9
10
11
12
Crew

Spatially-modulated auditory alerts

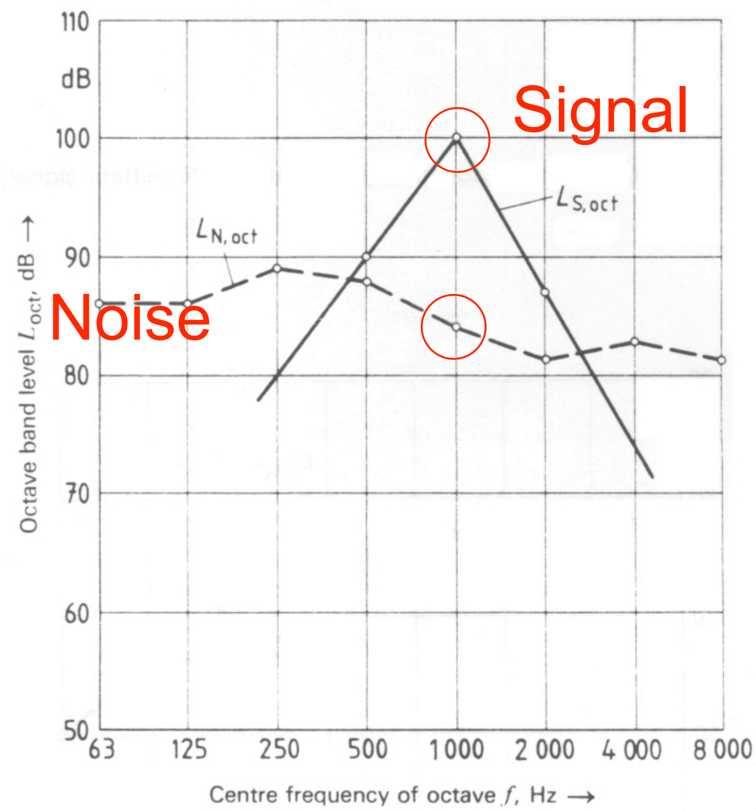
In an auditory display, how to insure that an alarm is audible?

-"Common sense" engineering approach: make the alarm *a lot louder* than the background noise for wide-area coverage

Fire alarm and horn from ca. 1933

In an auditory display, how to insure that an alarm is audible?

-ISO 7731 ("Danger signals for work places-Auditory danger signals") specifies signal to be >= 13 dB re masked threshold in a 1/3 octave band (0.3-3.0 kHz)



-Recipe for "startle effect", high overall SPLs, *and potentially low performance in a high-stress environment*

Current approach

-Improve detection of an alarm (signal) against ambient sound (noise) using signal processing techniques other than level increase

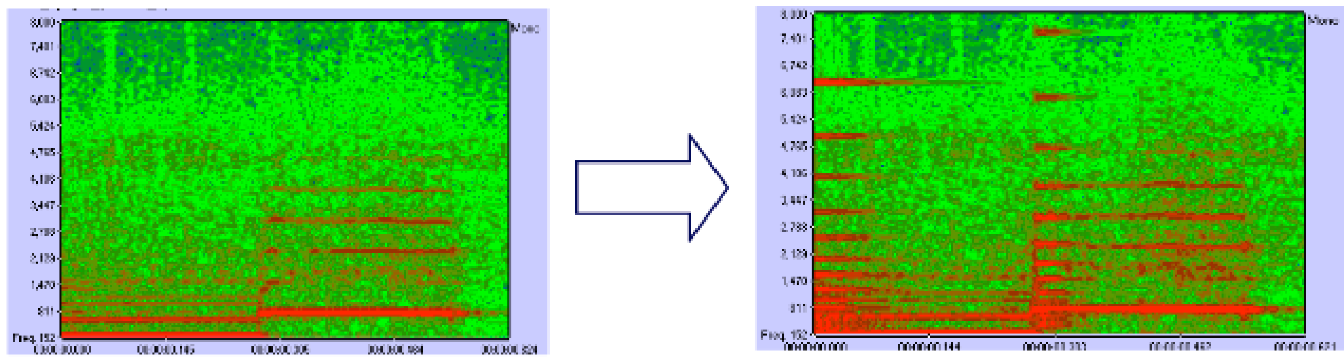
Requirement / Caveat

-Technique should apply to currently-used alarms (to avoid “relearning” semantic content of new auditory signals).

Technique

-Three methods addressed in patent application (pending) for accomplishing this.

Three techniques for improving detection of an existing alarm:

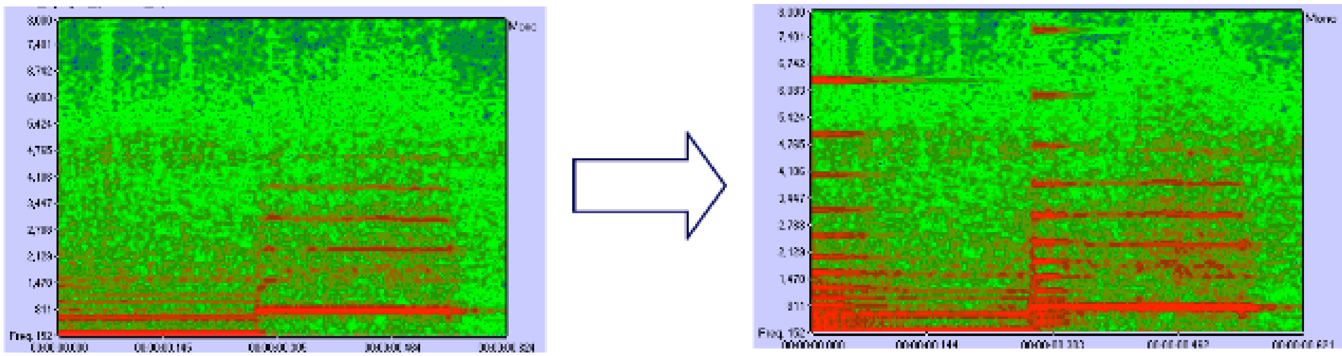


EXISTING 2-TONE ALARM ("GLIDESLOPE")

SAME ALARM "SPECTRALLY INFUSED" TO ENHANCE DETECTABILITY

1. Spectral infusion *(inspired by violin “pizzicato-arco”)*
(to be covered in a future paper)

Three techniques for improving detection of an existing alarm:



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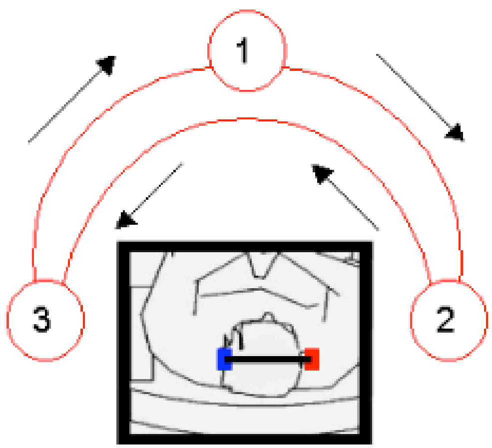


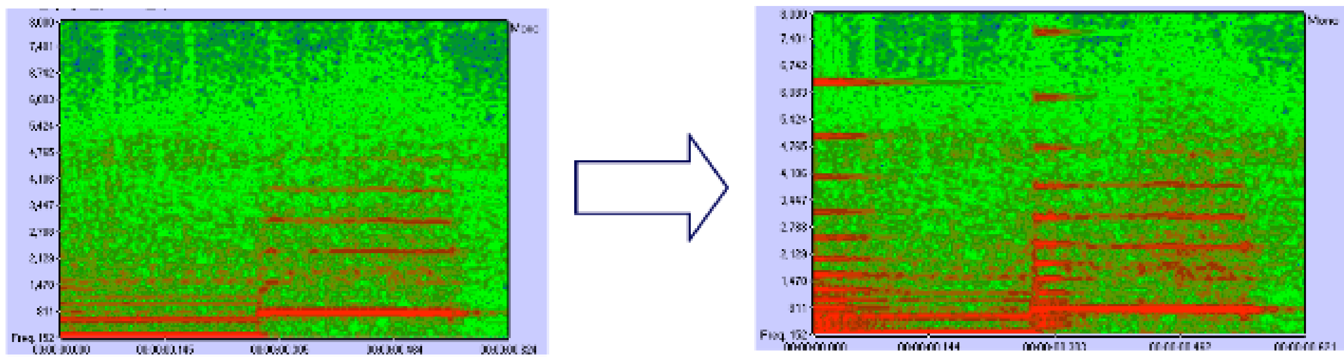
SPATIAL MODULATION OF ALARM

(2-10 Hz modulation)

2. Spatial modulation *(inspired by annoying insects)* within the rate of binaural sluggishness (to emphasize motion detection over localization)

Topic of this presentation

Three techniques for improving detection of an existing alarm:



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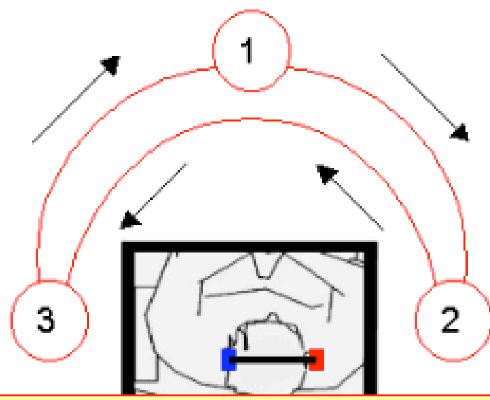
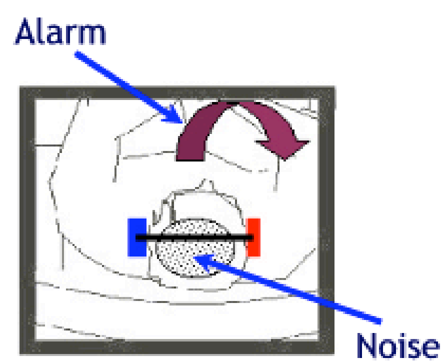


3. Increased noise correlation *(future paper)*



CORRELATE BACKGROUND NOISE

Main experimental goals

-Determine effect of spatial modulation rate (using HRTF-based spatial panning technique) for signal detection

-Determine if results obtained from virtual presentation of signal & noise sources differs from using real loudspeakers

Experiment design

-Six conditions for planned comparisons, varying sound source for noise and alert, and level of spatial modulation

-Fourteen subjects

-Within-subject design

-Each condition run twice (12 blocks / subject)

Block type	Noise Source	Alert Source	Spatial Modulation (Hz)
1	Loudspeaker	Loudspeaker	0
2	Loudspeaker	Headphone	1.66
3	Loudspeaker	Headphone	3.33
4	Headphone	Headphone	0
5	Headphone	Headphone	1.66
6	Headphone	Headphone	3.33

Main Independent variables

- Spatial modulation (“jitter”) rate of target stimulus:
  0, 1.6, or 3.3 Hz

- Virtual versus real loudspeaker simulation of background
  noise and alert

- Headphone versus loudspeaker presentation of alert

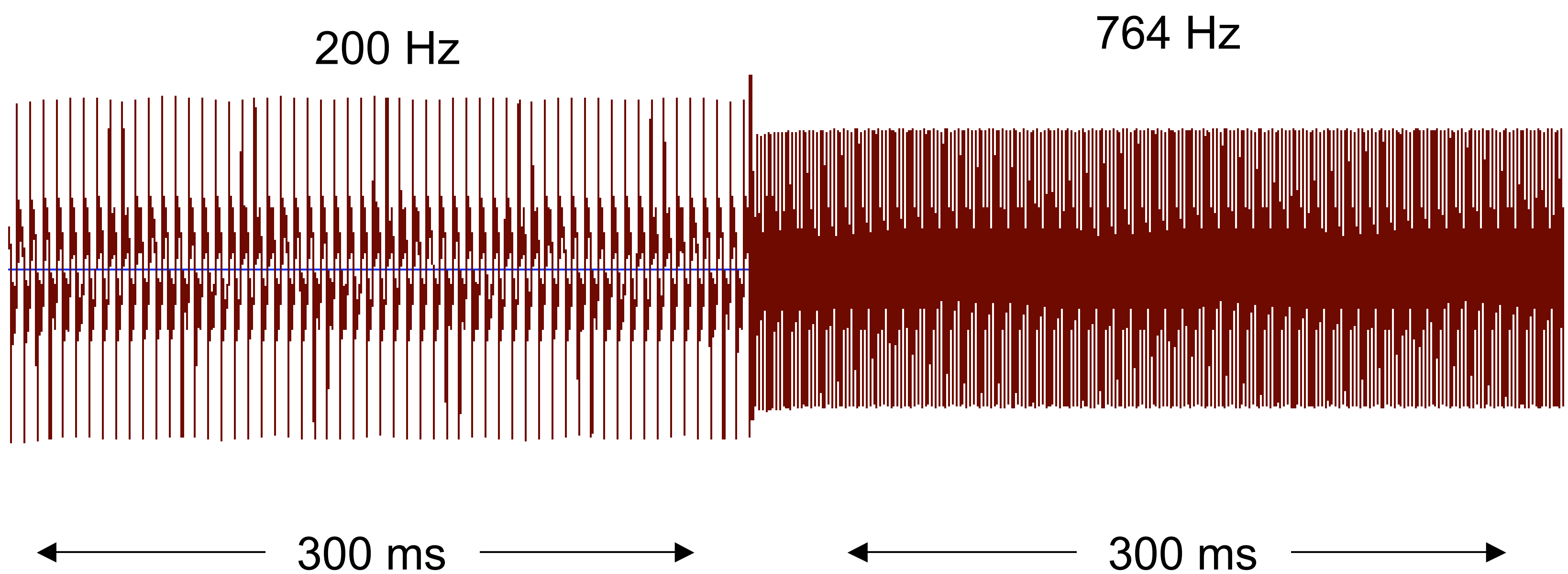
Common dependent variable

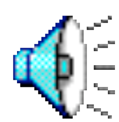
- 70.7 % threshold level for detection of the alert

(measured via 2-AFC, 1 up- 2 down adaptive staircase
within 1 dB tolerance)

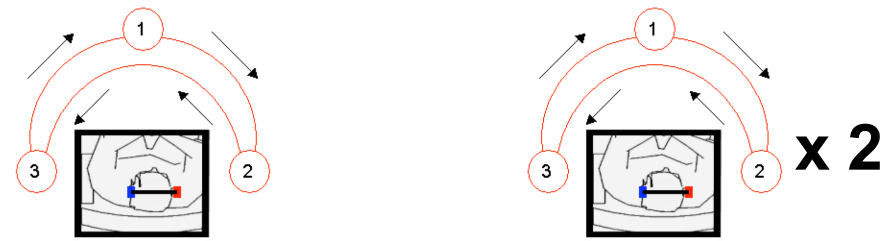
Alarm (basic stimulus)

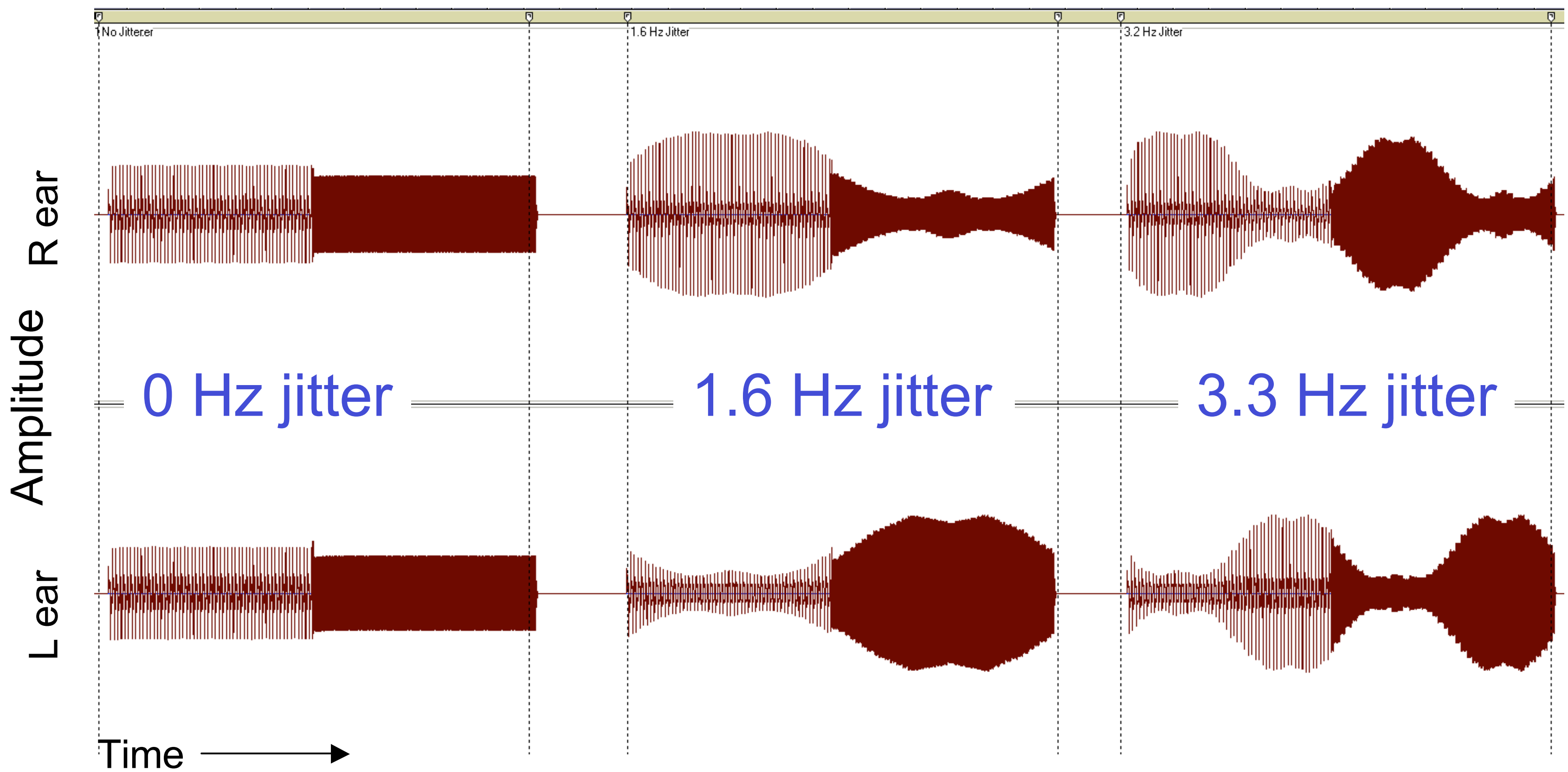
737-300 alarm: Two successive square waves
(preceding verbal “wind sheer” alert)





Stimuli

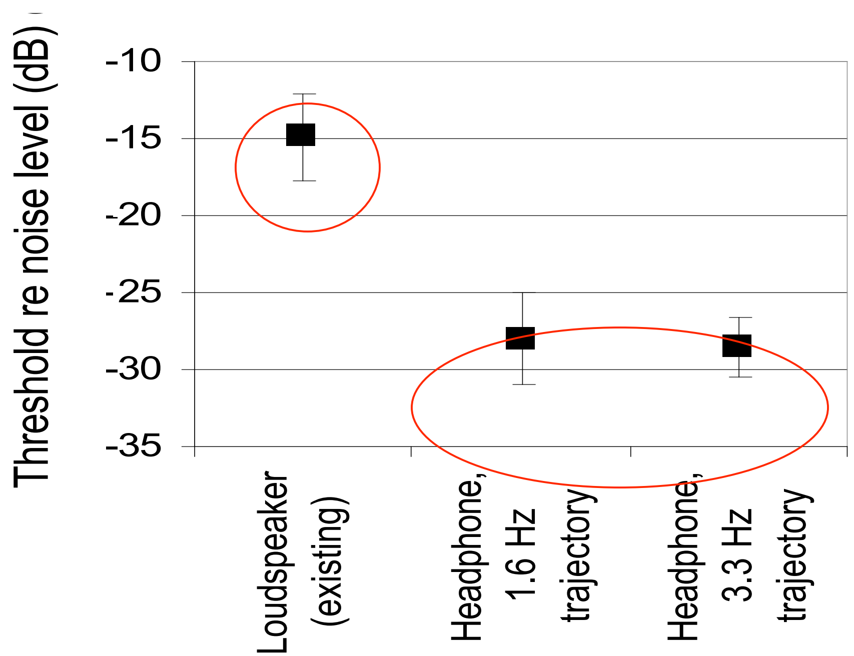




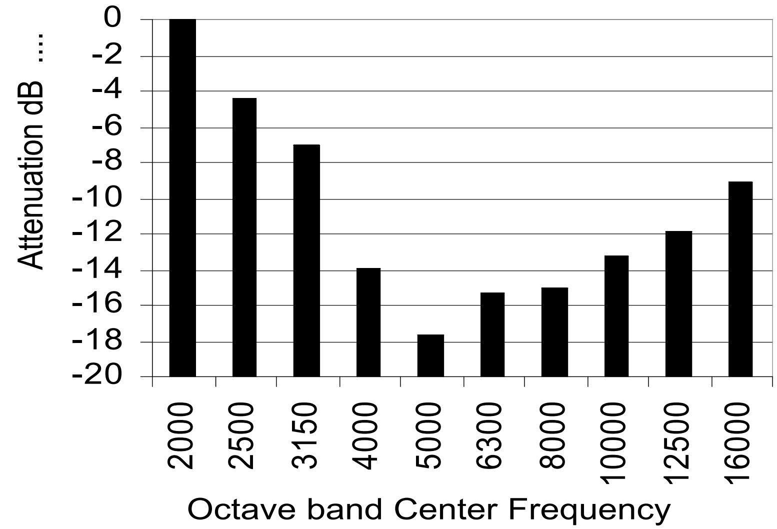
Summed L+R RMS levels equivalent for all stimuli; but jittered stimuli have + 5 dB peaks *re* unjittered due to HRTF.

Results (1)

Headphone with jittered signal has 13.4 dB advantage over monaural loudspeaker (existing condition on aircraft), partly due to attenuation of noise by headphone



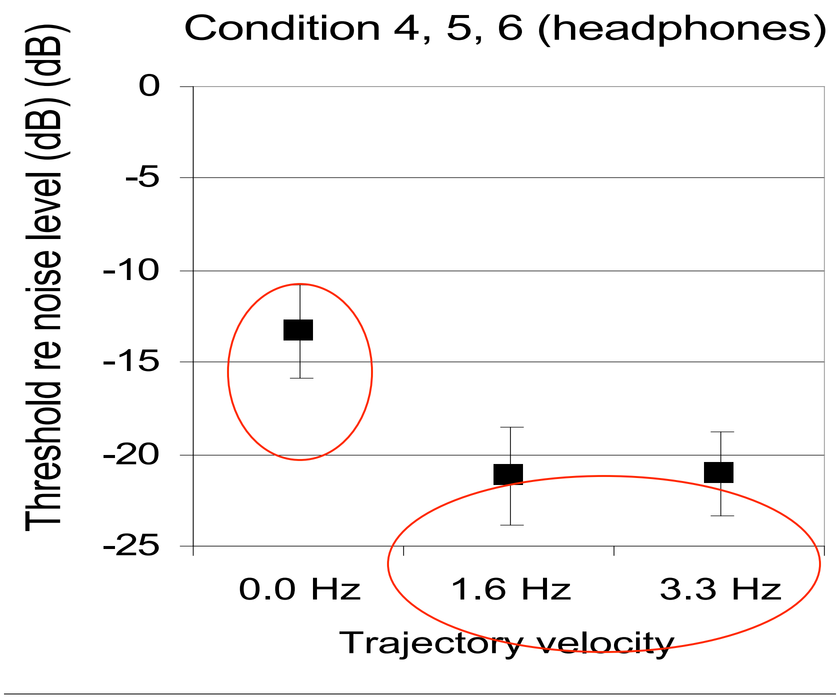
Results



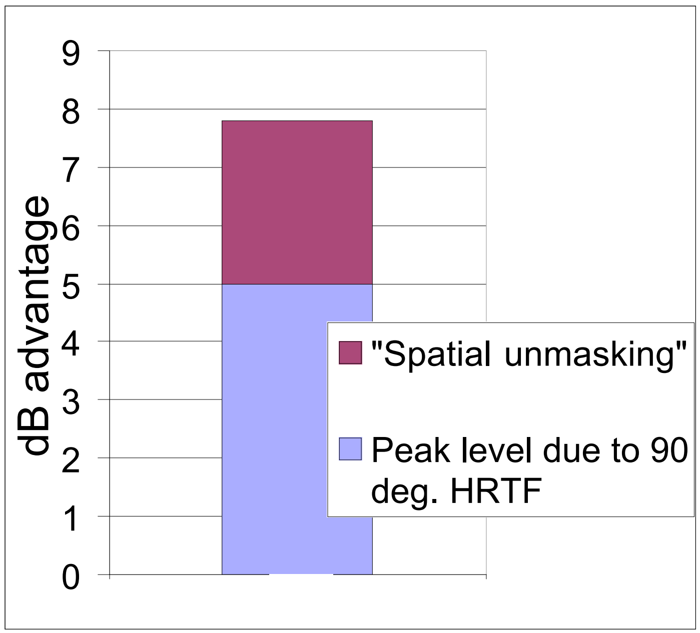
Headphone attenuation
Sennheiser HD 480 vented

Results (2)

Headphone with jittered signal has significant *(p < .000)* 7.8 dB advantage over headphone without jittered signal.
No significant difference between 1.6 and 3.3 Hz modulation.



results



source of unmasking (?)

Conclusions

A new approach to designing alerts for auditory displays in high-stress interfaces: use of spatial modulation for improved detection.

Headphones + spatial modulation lower threshold by 13.4 dB.

Spatial modulation lowers threshold by 7.8 dB.
5 dB is due to HRTF interaural level difference **if** instantaneous (peak) level differences are assumed. This amount is reduced as a function of longer temporal integration periods. Remaining advantage is due to time varying interaural cross-correlation.

BINAURAL LOCALIZATION

- **IMMEDIATE SITUATIONAL AWARENESS (WITH HEADS-UP ADVANTAGE)**
- **ALTERNATIVE or REDUNDANT DISPLAY for VISUALLY-ACQUIRED INFORMATION**

+

THE "COCKTAIL PARTY" EFFECT

- **INTELLIGIBILITY IMPROVEMENT**
  Binaural release from masking
- **DISCRIMINATION and SELECTIVE ATTENTION IMPROVEMENT**

+

ACTIVE NOISE CANCELLATION

HEARING CONSERVATION

=

Benefits: increased aviation safety & efficiency